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ON THE OPTIMIZATION OF REFRIGERATION MACHINERY

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Abstract

We present the application of thermoeconomics to the optimization of a model of a single-stage heat pump cycle. The method is well suited for application to thermodynamic processes and yields exergy losses. The marginal cost of an arbitrary variable can also be calculated. The efficiencies of the compressor, condenser, evaporator, and electric motor are chosen as the decision variables which are to be optimized. Parameters such as the price of electricity, the temperature of the delivered heat, and the operation time may vary among optimizations, and results are presented for different parameter values. The result shows that the efficiency of the electric motor is most important.

OPTIMISATION THERMIQUE ET ECONOMIQUE D'UN SYSTEME DE POMPE A CHALEUR MONO-ETAGE

RESUME : Cet article présente l'application d'une étude thermique et économique de l'optimisation d'un modèle de cycle de pompe à chaleur mono-étage. Cette méthode convient bien à l'application aux processus thermodynamiques et donne peu de pertes d'exergie. Le coût marginal d'une variable arbitraire peut aussi être calculé. Les rendements du compresseur, du condenseur, de l'évaporateur et du moteur électrique sont choisis comme les variables de décision à optimiser. Des paramètres tels que le prix de l'électricité, la température à laquelle la chaleur est fournie et le temps de fonctionnement peuvent varier suivant les optimisations ; les résultats sont présentés pour différentes valeurs des paramètres. Le résultat montre que le rendement du moteur électrique est le plus important.

ON THE OPTIMIZATION OF REFRIGERATION MACHINERY†

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INTRODUCTION

Contemporary technical systems are often constructed without detailed prior analysis of the effects of different potential solutions for a given system in terms of cost. Instead, constructions are often based on experience, educated guesswork and personal evaluations. Irrespective of the method used, the maximum cost permitted for each part of the system is obtained, and the market prices then determine to what extent efficient components can be afforded. Such systems always cost at least as much as and often more than they would if thermoeconomic optimization were used.

Tribus and El-Sayed^{1,2} developed the concept of thermoeconomics, in which the objective function is optimized, subject to given economic and technical constraints. The purpose of thermoeconomics is to improve analyses of systems by introducing ways of concurrently suggesting improvements.

The result of an insufficient analysis is that we never know the best solution or how to find it. By optimizing the total system in operation, we always find the best system within the given conditions. We can also calculate the marginal costs of the exergy losses in each component. These values are very important in the selection of research and development measures, or in the improvement of an existing system.

The system is described in relation to the physical (pressure p_0 , temperature T_0 , and chemical potentials of the appropriate substances $m_{e,0}$) and economic environments (prices of goods c_i and prices of capital or interest rates a_i). These two environments are interrelated by cost relations for physical quantities, see Fig. 1.

Fig. 1. The system in two environments.

With regard to the physical environment, the energy and mass flows are evaluated in physical terms, i.e., in terms of exergy per unit time.³ The difference between all incoming exergy flows and all outgoing exergy flows must be minimized and the efficiency must be maximized. In the economic environment all energy and mass flows are evaluated instead in terms of economic value or costs. The main function is now the cost per unit time, (i.e., operation and capital costs minus income), which should be minimal. Thermoeconomic optimization is economic optimization in conjunction with thorough thermodynamic description of the system.

†The author's thesis which includes all computer programs together with other papers³ and a bibliography of more than 1400 references on exergy is available by sending USD 20 per copy to: Göran Wall, Physical Resource theory, Chalmers University of Technology, S-412 96 Göteborg, Sweden.

EXERGY

The exergy losses due to irreversibilities in a stationary state can be determined for each zone, a single component or a number of components, by regarding in and outflows of exergy. The exergy content E of a flow is

$$E = H - T_0 S - \sum_c \mu_{c,0} n_c, \quad (1)$$

where H is the enthalpy, T_0 the absolute temperature of the environment, S the entropy, and $\mu_{c,0}$ the chemical potential of substance c of quantity n_c . The exergy loss can be determined for each zone. For the system, we obtain a sum for all zones, which gives the total rate of exergy loss. This may also be written as the product of the environment temperature and total rate of entropy production, i.e., $T_0 \Delta S_{tot}$.³

REFRIGERATION MACHINERY

Heat pump systems offer much more efficient means of producing heat than traditional combustion or electrical short circuit technologies. Heat pump systems are therefore becoming more common as the prices of fuels and electricity increase. The configuration of the system is defined in Fig. 2. It consists of a compressor, a condenser, an expansion valve, an evaporator, and an electric motor.

Fig. 2. Heat pump system with 5 components and 11 flows.

The refrigerant is superheated after passing through the evaporator, step 1-2, and supercooled after passing through the condenser, step 5-6. The actual state of the refrigerant after the compression, 3, differs from that of a reversible process, 3_{rev} , due to the limited efficiency of the compressor. The heat produced from the system is $h_3 - h_6$, the heat input is $h_2 - h_7$, and the work supplied to the compressor is $h_3 - h_2$. The electricity input required to operate the system becomes $(h_3 - h_2)/\eta_5$, where η_5 is the efficiency of the electric motor.

The system is completely defined apart from the variables $\{y_k\}$ which are the efficiencies of the compressor, the condenser, the evaporator, and the electric motor. These are defined as follows

$$y_1 = \eta_1 = (h_{3,rev} - h_2)/(h_3 - h_2), \quad (2)$$

$$y_2 = \eta_2 = (T_9 - T_8)/(T_4 - T_8), \quad (3)$$

$$y_3 = \eta_4 = (T_{11} - T_{10})/(T_1 - T_{10}) \quad (4)$$

$$y_4 = \eta_5 = m_r (h_3 - h_2)/P \quad (5)$$

where m_r is the mass flow of the refrigerant, and P is the electric power. Each set of these variables determines a state of the system. The exergy flows and exergy losses are also determined for each component.³

The objective is to minimize the cost for a given amount of produced heat. The cost includes both the operating (electricity) cost and the capital cost. The operating cost increases if the investments decrease and vice versa. The income from the product (heat) and a given required value of the profit sets an upper limit for the total cost of the system. The problem is to split this cost between the operating cost and the capital cost for each component. (The costs for parts not affected by alternative constructions of the system, such as pipes connecting the components, are just added as constants and have no effect on the optimization.) The costs, C , for each of the 5 components will now be given.

$$\text{Compressor} \quad C_1 = a_1 k_1 [V_2 / (0.9 - \eta_1)] (p_3 / p_2) [\ln(p_3 / p_2)] \quad (6)$$

where k_1 is the cost per volume flow, V_2 , and p_3/p_2 is the pressure ratio over the compressor.

$$\text{Condenser} \quad C_2 = a_2 k_2 m_{wh} \sqrt{\eta_2 / (1 - \eta_2)} = a_2 k_2 m_{wh} \sqrt{e^{NTU_2} - 1}, \quad (7)$$

where k_2 is the cost per mass flow of water, m_{wh} , on the hot side, and NTU_2 is the number of heat transfer units.

$$\text{Expansion Valve} \quad C_3 = a_3 k_3 m_r, \quad (8)$$

where k_3 is the cost per mass flow of the refrigerant.

$$\text{Evaporator} \quad C_4 = a_4 k_4 m_{wc} \sqrt{\eta_4 / (1 - \eta_4)} = a_4 k_4 m_{wc} \sqrt{e^{NTU_4} - 1}, \quad (9)$$

where k_4 is the cost per mass flow of water, m_{wc} , on the cold side, and NTU_4 is the number of heat transfer units.

$$\text{Electric Motor} \quad C_5 = a_5 k_5 P \eta_5 / (1 - \eta_5), \quad (10)$$

where k_5 is the cost per unit power. Furthermore a_1 to a_5 are annuity factors of the different capital investments defined as

$$a_i = r / [1 - (1 + r)^{-n_i}], \quad (11)$$

where r is the interest rate and n_i is the depreciation time for component i . The depreciation time may vary for each component due to variations in economic lifetime and maintenance costs such as renovations, etc.

Figure 3 shows the investment costs as a function of the efficiencies. The following assumptions are made: heat produced 6.5 kW (energy-power), operation time/yr 5000 hr, price of electricity SEK 0.25/kWh (SEK 6 $\approx$ US\$ 1), and temperature of the produced heat (T_3) 60°C.

Fig. 3. Costs of investments as a function of the efficiencies.

The investment costs are depreciated according to the annuity method, which gives a cost per unit time for every component. The total cost per unit time Φ_0 (= objective function) is the sum of these costs and the cost of the electricity used, E_{el} , i.e.,

$$\Phi_0 = \sum_{i=1}^5 C_i + t p_{el} E_{el}, \quad (22)$$

where t is the operating time per unit time and p_{el} is the price of electricity.

RESULTS AND CONCLUSIONS

The optimization is achieved by calculating the value of the objective function Φ_0 and the marginal costs $\{\theta_k\}$ for every set of the variables $\{y_k\}$ according to

$$\theta_k = \Delta\Phi_0/\Delta y_k, \quad k = 1, 2, 3, 4. \quad (23)$$

From these values a new set of variables $\{y_k\}$ is determined by using the Newton-Raphson method.⁴ Thus the system moves towards the nearest minimum from the given start values. However, the problem is strongly non-linear which means that there is no general method for finding the global minimum. Instead common sense and insight into how the system works must be used to determine the value of a solution.

A computer program has been developed for finding the optimum system.³ The program begins by calculating the thermodynamic data for the assumed refrigerant R12. (Other refrigerants may also be used.) These calculations are based on similar computer-based calculations by Reynolds.⁵ The equations of state for the system are formulated so as to avoid iterations. The actual minimizing procedure is carried out with a small number of iterations. When the sum of the marginal costs is less than a predefined value the optimization is completed.

Let us assume a system with the values 0.7, for all efficiencies, which roughly correspond to real values of a system of this size, the variables, which are to be optimized. The calculated total cost then becomes SEK 4221/yr of which SEK 3617/yr relate to electricity. The optimization gives the following efficiency values: compressor 0.80, condenser 0.83, evaporator 0.73 and electric motor 0.91, the total cost now amounting to SEK 3388/yr of which SEK 2416/yr is for the electricity. By increasing the investments from SEK 604/yr to SEK 972/yr, the total cost of the system becomes SEK 833/yr (about 20%) less than for the assumed system, see Fig. 4. At the same time the exergy losses decrease from 1933 W to 979 W, i.e., 954 W! From Fig. 5 we see that it is the improvement of the electric motor that gives the largest single exergy saving. The optimization saves both money and exergy.

Fig. 4. Costs for the assumed and the optimum systems.

Fig. 5. Exergy losses for the assumed and the optimum systems.

The expansion valve accounts for the largest exergy loss in the optimum system, which justifies investment in research and development to improve it.⁶

The result indicates the electric motor to be the most critical component to improve. The electric motor is assumed to cost approximately 3 times as much at 91% efficiency than at 70% efficiency, which must

be regarded as realistic. (However, it may even cost up to 9 times as much and still be competitive with the assumed system.) It may also be added that the coefficient of performance (CoP) increases from 2.25 for the assumed system to 3.36 for the optimal system.

The dependence on or sensitivity to the cost of electricity, the temperature of the produced heat, and the operation time has also been studied. Figure 6 shows the relationship between the costs and the price of electricity, when this varies between SEK 0.15 and 0.6/kWh. The total cost then increases from SEK 2073/yr to SEK 5522/yr at SEK 0.6/kWh. This can be seen in relation to the fact that if the optimum system at SEK 0.15/kWh had been used at SEK 0.6/kWh, then the total cost would be SEK 5947, i.e., an increase in the cost of SEK 425/yr. (For the assumed system the total cost would instead be SEK 9284, i.e., a cost increase of SEK 3762/yr.) Figure 7 shows more clearly the relationship between component costs and the price of electricity. All components should become more efficient (and therefore more expensive) when the price of electricity increases. This might have been anticipated, but the exact interrelations could not have been hypothesized.

Fig. 6. Costs as a function of the price of electricity.

Fig. 7. Component costs as a function of the price of electricity.
(The jerks in the curves are due to the limited number of data points.)

When the temperature of the condenser, i.e., the temperature of the produced heat, is changed interesting things occur (Figs 8 and 9). The total cost doubles from 2336 at 40°C to SEK 4680/yr at 75°C. The heat produced in energy per time units is the same, i.e., 6.5 kW, but in exergy per time units it changes from 434 to 713 W which better explains the increased cost. When the temperature increases from 40 to 75°C the total system, but not necessarily each component, must be more efficient see Fig. 9. Within a total increase of component costs and efficiencies, it is more economical to choose a less expensive evaporator. The explanation is simply that investments in other parts of the system pay off better.

Fig. 8. Costs as a function of the temperature of the produced heat.

The system is also very sensitive to the operating time which is shown in Figs 10 and 11.

Similarly, all other relations may be described using the computer program for the system. The program can easily be rewritten for other refrigerants or cost relations. The purpose of this study is merely to show the gain achieved by applying the method of thermoeconomics to an example of a refrigeration machinery. The exact numerical results for describing thermoeconomics as a method for improving technical processes have therefore been neglected.

Fig. 9. Component costs as a function of the temperature of the produced heat.

Fig. 10. Costs as a function of the operating time.

Fig. 11. Component costs as a function of the operating time.

But, thermoeconomics can never replace long experience and high technical and economic competence, but it might be an important complementary tool.

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